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Exhibit E

# Schmitt Trigger

## Introduction

Sometimes an input signal to a digital circuit doesn't directly fit the description of a digital signal. For various reasons it may have slow rise and/or fall times, or may have acquired some noise that could be sensed by further circuitry. It may even be an analog signal whose frequency we want to measure. All of these conditions, and many others, require a specialized circuit that will "clean up" a signal and force it to true digital shape.

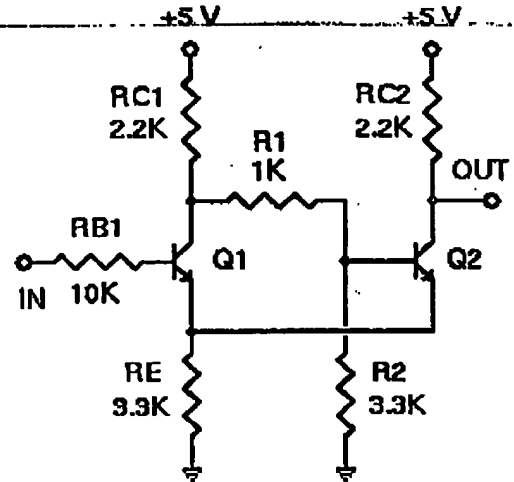
The required circuit is called a *Schmitt Trigger*. It has two possible states just like other multivibrators. However, the trigger for this circuit to change states is the input voltage level, rather than a digital pulse. That is, the output state depends on the input level, and will change only as the input crosses a pre-defined threshold.

In this experiment, we will look at the theory of this circuit's operation, and then build one to demonstrate its real-world operation.

## Schematic Diagram

Unlike the other multivibrators you have built and demonstrated, the Schmitt Trigger makes its feedback connection through the emitters of the transistors as shown in the schematic diagram to the right. This makes for some useful possibilities, as we will see during our discussion of the operating theory of this circuit.

To understand how this circuit works, assume that the input starts at ground, or 0 volts. Transistor Q1 is necessarily turned off, and has no effect on this circuit. Therefore, RC1, R1, and R2 form a voltage divider across the 5 volt power supply to set the base voltage of Q2 to a value of  $(5 \times R2)/(RC1 + R1 + R2)$ . If we assume that the two transistors are essentially identical, then as long as the input voltage remains significantly less than the base voltage of Q2, Q1 will remain off and the circuit operation will not change.



**Note:** Classical analyses of this circuit include the forward current gain,  $h_{FE}$ , of the two transistors. This was important in the early days of transistors when a signal transistor was doing well to have a current gain of 30. Modern transistors have a much higher gain (160 for the 2N3904/2N3906, 200 for the 2N4124/2N4126), so they don't have the same limitations as older transistors. We can ignore the effects of transistor base current, although we do still need to account for  $V_{BE}$  for the two transistors.

While Q1 is off, Q2 is on. Its emitter and collector current are essentially the same, and are set by the value of RE and the emitter voltage, which will be less than the Q2 base voltage by  $V_{BE}$ . If Q2 is in saturation under these circumstances, the output voltage will be within a fraction of the threshold voltage set by RC1, R1, and R2. It is important to note that the output voltage of this circuit cannot drop to zero volts, and generally not to a valid logic 0. We can deal with that, but we must recognize this fact.

Now, suppose that the input voltage rises, and continues to rise until it approaches the threshold voltage on Q2's base. At this point, Q1 begins to conduct. Since it now carries some collector current, the current through RC1 increases and the voltage at the collector of Q1 decreases. But this also affects our voltage divider, reducing the base voltage on Q2. But since Q1 is now conducting it carries some of the current flowing through RE, and the voltage across RE doesn't change as rapidly. Therefore, Q2 turns off and the output voltage rises to +5 volts. The circuit has just changed states.

If the input voltage rises further, it will simply keep Q1 turned on and Q2 turned off. However, if the input voltage starts to fall back towards zero, there must clearly be a point at which this circuit will reset itself. The question is, What is the falling threshold voltage? It will be the voltage at which Q1's base becomes more negative than Q2's base, so that Q2 will begin conducting again. However, it isn't the same as the rising threshold voltage, since Q1 is currently affecting the behavior of the voltage divider.

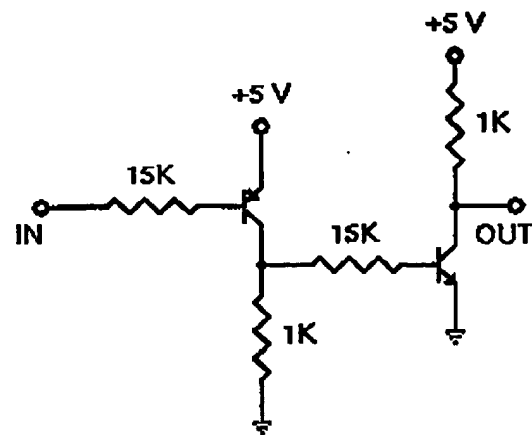
We won't go through all of the derivation here, but when  $V_{IN}$  becomes equal to Q2's base voltage, Q2's base voltage will be:

$$V_{B2} = \frac{5 + V_{BE} \frac{RC2}{RE}}{1 + \frac{RC1}{RE} + \frac{RC1 + R1}{R2}}$$

As  $V_{IN}$  approaches this value, Q2 begins to conduct, taking emitter current away from Q1. This reduces the current through RC1 which raises Q2's base voltage further, increasing Q2's forward bias and decreasing Q1's forward bias. This in turn will turn off Q1, and the circuit will switch back to its original state.

Three factors must be recognized in the Schmitt Trigger. First, the circuit will change states as  $V_{IN}$  approaches  $V_{B2}$ , not when the two voltages are equal. Therefore  $V_{B2}$  is very close to the threshold voltage, but is not precisely equal to it. For example, for the component values shown above,  $V_{B2}$  will be 2.54 volts when Q1 is held off, and 2.06 volts as  $V_{IN}$  is falling towards this value.

Second, since the common emitter connection is part of the feedback system in this circuit, RE must be large enough to provide the requisite amount of feedback, without becoming so large as to starve the circuit of needed current. If RE is out of range, the circuit will not operate properly, and may not operate as anything more than a high-gain amplifier over a narrow input voltage range, instead of switching states.



The third factor is the fact that the output voltage cannot switch over logic levels, because the transistor emitters are not grounded. If a logic-level output is required, which is usually the case, we can use a circuit such as the one shown here to correct this problem. This circuit is basically two RTL inverters, except that one uses a PNP transistor. This works because when Q2 above is turned off, it will hold a PNP inverter off, but when it is on, its output will turn the PNP transistor on. The NPN transistor here is a second inverter to re-invert the signal and to restore it to active pull-down in common with all of our other logic circuits.

The circuit you will construct for this experiment includes both of the circuits shown here, so that you can monitor the response of the Schmitt trigger with L0.

## The Trimmer Potentiometer

A new component that you will need for this project is a trimmer potentiometer. A potentiometer consists of a resistive element with a movable electrical contact touching it. This permits the potentiometer to serve as a continuously-variable voltage divider.



The figure to the right shows one of the many kinds of potentiometers available for a wide range of applications. This one uses a screw to slowly advance the moving contact along the resistance element. This allows accurate placement of the contact and reduces the likelihood that an accident may move the contact away from the desired position. The particular potentiometer that we will use requires 15 turns of the screw to cover the entire resistance range.

This particular type of potentiometer is typically known as a *trimmer potentiometer* (or *trimpot* for short), because it is intended to be adjusted or "trimmed" to a particular setting, and then left there to retain its setting. It will seldom need to be readjusted in normal use.

## Parts List

To construct and test the Schmitt Trigger circuit on your breadboard, you will need the following

*Attorney Docket No.:* 42.P10109

*Application No.:* 09/996,255

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X. RELATED PROCEEDINGS APPENDIX

None.